Internal Waves in Straits Experiment

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Award Number: N00014-091-0273
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LONG-TERM GOALS

To understand the generation, propagation and dissipation of large amplitude internal tides.

OBJECTIVES

To obtain time series and spatial structure of internal tidal propagation and evolution westward from the ridges in Luzon Strait during the Internal Waves in Straits Experiment (IWISE).

APPROACH

Spatial and temporal variability of internal tidal generation and propagation may arise due to either changing background conditions (i.e., stratification, vorticity, mesoscale currents, and the Kuroshio Current) or interference patterns from multiple generation sites on the complex topography. Some of

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE **Internal Waves in Straits Experiment**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of California, San Diego,Scripps Institution of Oceanography,9500 Gilman Drive,San Diego,CA,92093**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

the largest internal tides in the ocean, with depth-integrated energy fluxes >60 kW m^{-1}, are generated at two parallel ridges in Luzon Strait (Alford et al., 2011; Simmons et al., 2011). Averaging over many glider missions, considerable asymmetry is found between eastward and westward propagation into the Pacific Ocean or South China Sea (Rainville et al., 2013; Rudnick et al., 2013). Here we focus on the waves, which propagate westward into the South China Sea, steepen, and produce large-amplitude internal waves on the shallow thermocline. Our work is a component of the Internal Waves in Straits Experiment (IWISE).

In the face of such variability, extensive spatial coverage in the South China Sea and temporal coverage over spring-neap cycles is required to assess the generation and propagation of internal tides away from Luzon Strait. Two Spray underwater gliders, each equipped with an acoustic Doppler profiler (ADP) a conductivity-temperature-depth instrument (CTD), obtained internal tidal energy flux from tidally-resolving density and velocity measurements in the South China Sea. To our knowledge, this work is the first such calculation of energy flux from underwater gliders (Figures 1–2).

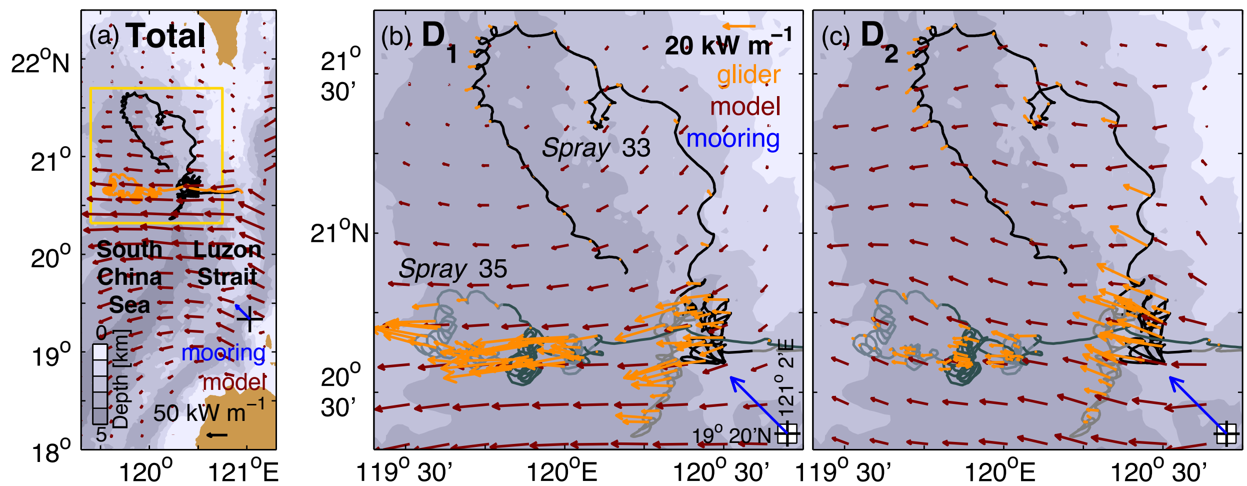

Figure 1: (a) Time-averaged, depth-integrated, mode-1 energy fluxes of 40–50 kW m^{-1} are generated at the ridges in Luzon Strait and propagate into the South China Sea from the model (red) and mooring (blue). Glider tracks (black and orange for *Spray* ***33 and 35), mooring location (cross), and the region (yellow) in Figures 1b–c are also indicated. Bathymetry (grey shading), land (brown shading), and a scale vector are shown. (b) For D_1 and (c) D_2 constituents, depth-integrated, mode-1, baroclinic energy fluxes in the South China Sea are measured over spring and neap cycles by the gliders (orange) and are a one month time average from the model (red) and time-mean from the mooring (blue) over roughly the same period as the gliders. Glider fluxes are plotted at 1-day intervals. The glider tracks are plotted with alternating lighter and darker colours corresponding to alternating colours on the time axes in Figure 2. The mooring lies further south and the vector is inset (lower right).***

WORK COMPLETED

Two gliders observed the internal tide over four spring-neap cycles (13 June–8 August 2011) in the South China Sea. At five nominal sites along 20° 39′N, time series were obtained with each covering a spring-neap cycle. One glider took advantage of strong northward mean currents and surveyed the

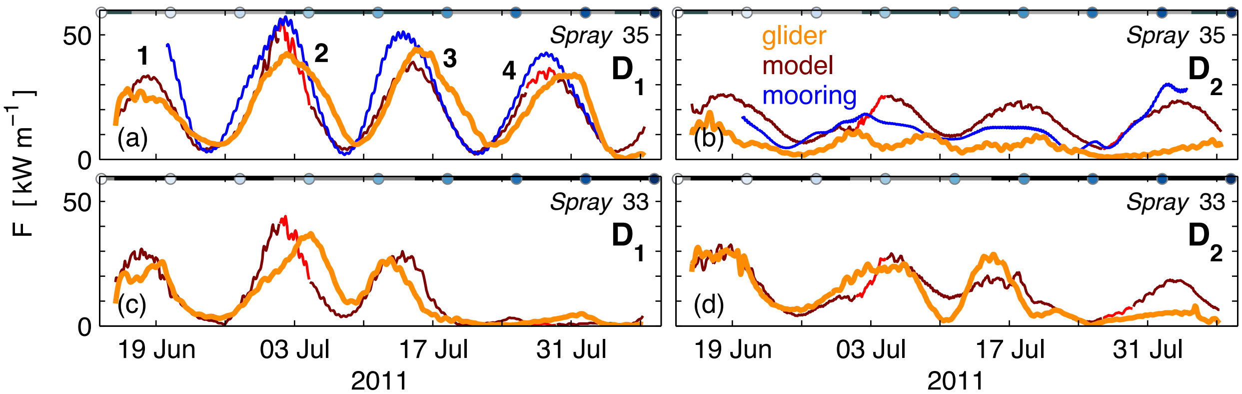

Figure 2: Depth-integrated, mode-1 energy flux magnitude from (a–b) Spray 35 and (c–d) Spray 33 for D_1 (left) and D_2 (right) are generally westward (Figure 1). Line colours denote gliders (orange), model (red), or mooring (blue). Spring tides are labelled 1–4 (Figure 2a). Areas of model overlap (light red) may suffer from edge effects.

northern South China Sea. This capability to relocate during a mission allows for coverage in space and time.

For this project, Spray sampled every 6 s (or vertically <1 m) during ascents (Sherman et al., 2001). The payload included: (a) a pumped Sea-Bird Electronics (SBE) 41CP CTD to obtain temperature and salinity, from which potential temperature, in situ density, and potential density are calculated and (b) a Sontek 750 kHz ADP aligned to measure horizontal velocities in five 4-m vertical range bins. Over 2 months, a total of 1312 profiles were completed. Data and times are averaged in 10-m bins centered from 10–500 m. To resolve tides, the gliders dove at an angle of 30° from 0–500 m in depth every $\sim$2 hours on average.

RESULTS

As our primary technical result, we calculate mode-1 energy fluxes from velocity and density measurements by gliders which profiled rapidly enough to resolve the tides in the upper 500 m. Time series at five fixed locations and even while moving provide regional coverage over the northern half of the South China Sea using two gliders. The main limitation in our method is the lack of glider data below 500 m, which is mitigated by the shallow thermocline, the strong mode-1 signal, and fitting mode 1 to tidal currents and displacements. During spring tides, westward diurnal (D_1) and semidiurnal (D_2) mode-1 fluxes exceed 40 and 30 kW m^{-1}. As long as the thermocline is shallow enough to permit mode-1 fits, gliders can survey regional areas for internal tides with mode-1 flux estimates once every few days for $\sim$2 months.

Perhaps the most interesting scientific result is that our phase estimates appear stable across 100 km and 2 months. This result is somewhat surprising given the vigourous mesoscale flows in this area and other processes affecting internal tidal generation and propagation, which generally produce a broad-banded internal tide. Consistent phase propagation over a 2-month mission highlights the narrow-banded nature of the internal tide in time, which also makes some of the calculations here possible. Another interesting feature is the roughly constant phase along some ray paths emanating from likely generation sites on both ridges in Luzon Strait even after one (three) reflection(s) for the D_1 (D_2) rays. Energy

density can be intensified along these ray paths, which are then called internal tidal beams to emphasize the larger displacement and velocity amplitudes (Holloway and Merrifield, 1999; Martin et al., 2006; Cole et al., 2009; Johnston et al., 2011). While constant phase (i.e., a wave crest) defines a ray path (Mowbray and Rarity, 1967), constant phase along a beam has been infrequently observed.

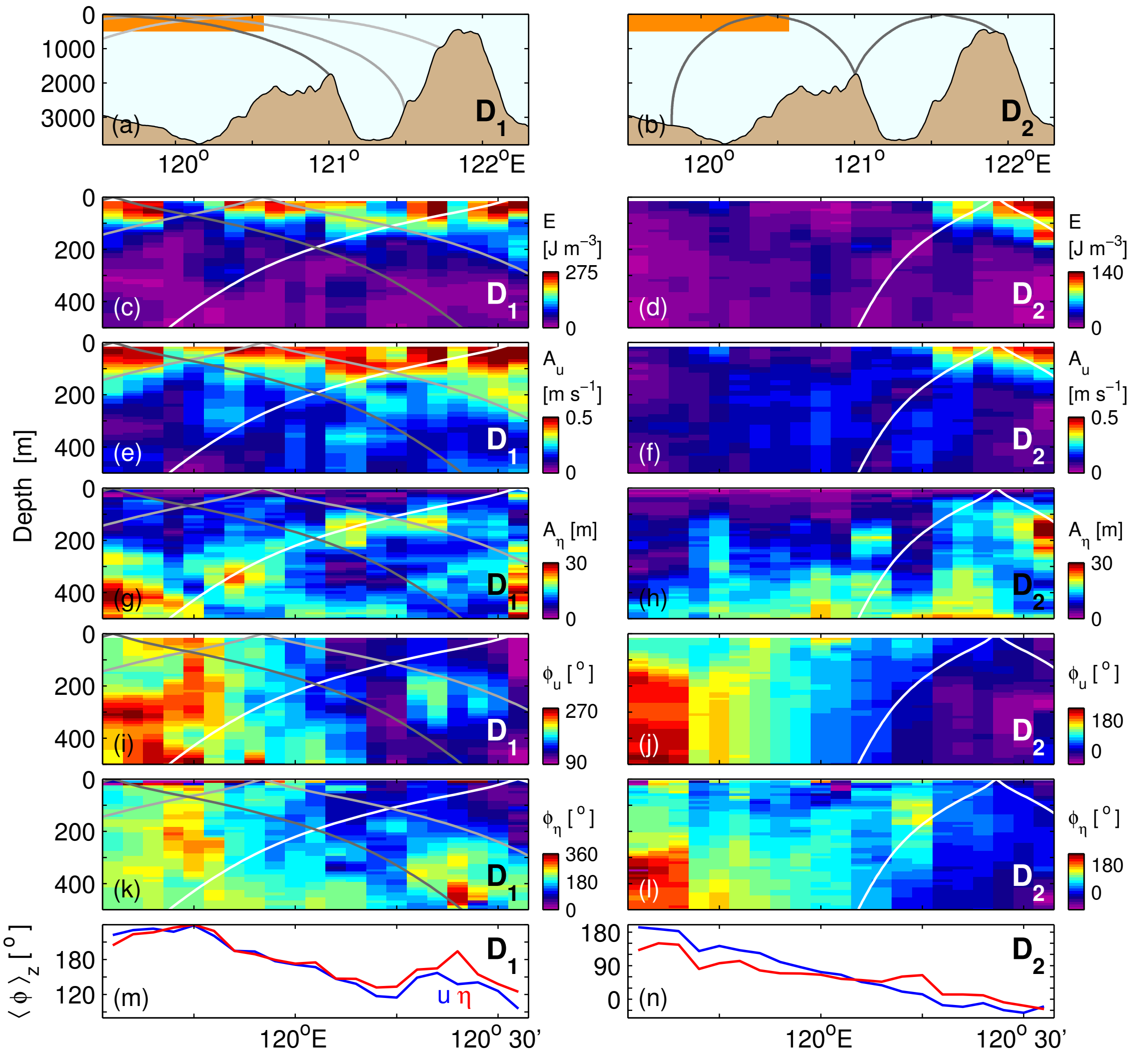

Figure 3: The vertical-zonal structure of the internal tide for D_1 (left column) and D_2 (right column) constituents is displayed. (a–b) Ray paths are traced to topography in Luzon Strait and are shown in the upper 500 m in the subsequent panels. Orange boxes (upper left) indicate the location of the glider data in subsequent panels. We calculate vertical-zonal bin means for (c–d) baroclinic energy density, (e–f) tidal amplitudes from the harmonic fits of u' and (g–h) η', and (i–j) tidal phases for u' and (k–l) η'. (m–n) Depth-mean phases for u' and η' are calculated from data in Figures 3i–l.

IMPACT/APPLICATIONS

In regions with relatively shallow thermoclines, gliders can assess mode-1 energy fluxes. Typically mode 1 carries much of the energy flux. The high-vertical resolution also allows calculation of phases, which appear stable over our time and space coverage of 2 months and 100 km. In other observational

efforts with gliders, phase has proven useful in diagnosing internal tidal propagation/reflection at the Tasman slope and trapping of the D_1 internal tide off the California coast.

RELATED PROJECTS

An ONR project with Sarkar (MAE, UCSD) is using observational guidance from a number of observations of beams including ONR's AESOP and IWISE initiatives to refine models showing turbulence in internal wave beams at (a) critical topographic slopes and (b) in the surface layer.

The NSF-funded Tasmanian Tidal Dissipation Experiment (TTIDE) with many IWISE PIs (Pinkel, Alford, Johnston, MacKinnon, Nash, Rainville, Rudnick, and Simmons) is investigating dissipation of an incident low-mode internal tide impinging on the steep continental slope of Tasmania. Preliminary results from one glider's spatial survey over $\sim$4 months shows a region of elevated tidal amplitudes and stable phase, which bears resemblance to preliminary model results. An analysis of incident and reflected waves, shows a stronger incident wave and weaker reflected one, which implies wave transmission onto the shelf and/or dissipation on the shelf. A second glider was deployed in August 2013 and is still in the water. The main experiment will be in 2015.

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